A 475-511GHz Radiating Source with SIW-based Harmonic Power Extractor in 40 nm CMOS

Kaizhe Guo and Patrick Reynaert
KU Leuven, ESAT-MICAS
Kasteelpark Arenberg 10, 3001 Leuven, Belgium
{Kaizhe.Guo, Patrick.Reynaert}@esat.kuleuven.be

***Abstract*—This paper presents a 0.49 terahertz (THz) radiating source in 40 nm CMOS. The radiating source is composed of a cross-coupled oscillator, a differential tripler, a substrate integrated waveguide (SIW) based harmonic power extractor (HPE) and a folded dipole antenna. The HPE can optimize third harmonic power extraction and provide suppression of unwanted lower order harmonic leakage. The measured equivalent isotropically radiated power (EIRP) of the radiating source is -4.1 dBm. According to simulated antenna gain of 11.2 dB, the output power and DC-to-THz efficiency of the signal source can be calculated as -15.3 dBm and 0.173%, respectively. The output frequency can be tuned from 475 to 511 GHz within 10 dB EIRP variation.**

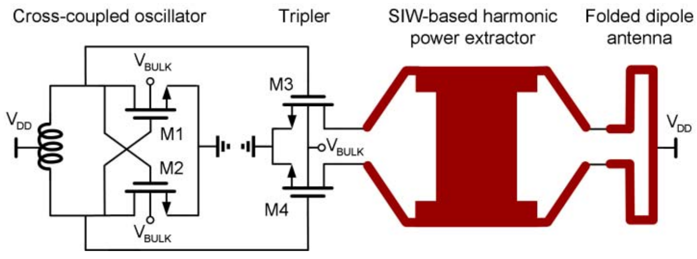
***Index Terms*—CMOS, terahertz radiation, substrate integrated waveguide (SIW), voltage-controlled oscillator(VCO).**

I. Introduction

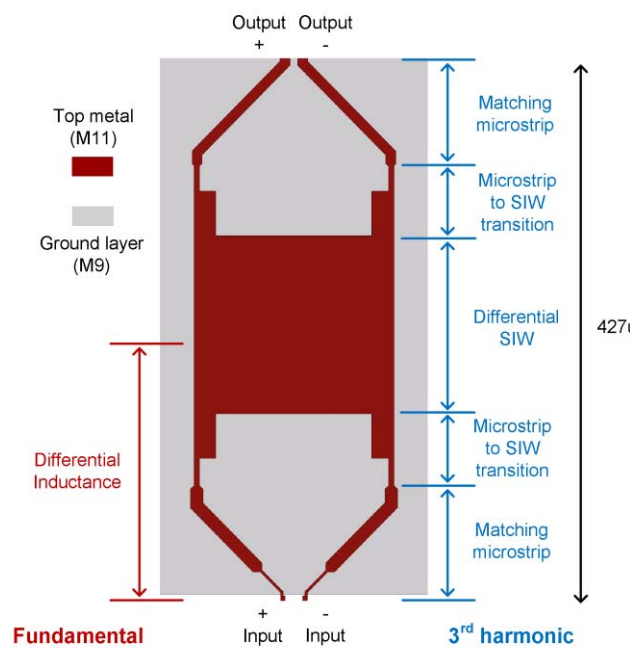
Due to the interaction of THz electromagnetic wave with different chemical components, it can be used for spectroscopy application [1]. To fulfill the requirement of this application, a THz signal source with wide frequency tuning range and high output power is needed. CMOS technology, because of its advantage of low cost in volume production, is a preferred technology for mass-produced THz chips. While more and more CMOS signal source designs below 350 GHz have been presented in recent years, there are limited signal source designs beyond 400 GHz [1]-[8].

Pushing output frequency of a signal source beyond 400 GHz is not trivial. First, the output power of a fundamental oscillator reduces with frequency so harmonic power extraction is needed to generate signals above $f_{\max}$. Secondly, using varactors for frequency tuning above 100 GHz lowers the achievable output power of a signal source [1].

To address those issues, a radiating source using an oscillator-tripler-HPE topology and bulk bias tuning technique is proposed. As shown in Fig. 1 (a), the radiating source is composed of a 163 GHz cross-coupled oscillator, a differential tripler, a differential SIW-based HPE and a folded dipole antenna. This topology has fully symmetrical layout and effectively produces third harmonic output power around 0.49 THz. The SIW-based HPE is proposed to optimize third harmonic power extraction and provide suppression of unwanted lower order harmonic leakage. Bulk bias tuning technique presented in [5] is utilized in this work to increase frequency tuning range.



(a)



(b)

Fig. 1. (a) Schematic of the 0.49 THz radiating source, (b) SIW-based harmonic power extractor.

II. SIW-based Harmonic Power Extractor

To effectively extract harmonic power, two aspects are important: harmonic generation and impedance matching at the harmonic frequency. In the proposed oscillator-tripler-HPE topology, thanks to the HPE, both functions are optimized. To maximize harmonic generation, load impedance seen by the tripler needs to be optimized at the fundamental frequency. At the same time, to provide matching for generated power, optimization of the tripler load impedance is also needed at the third

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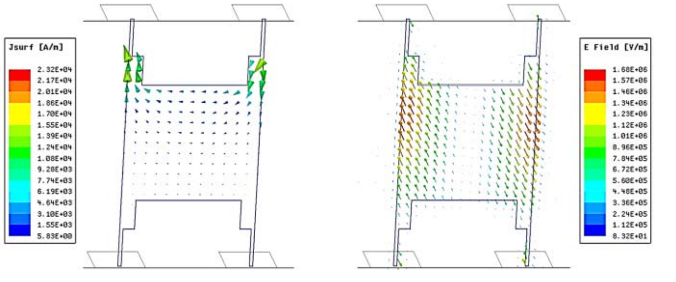
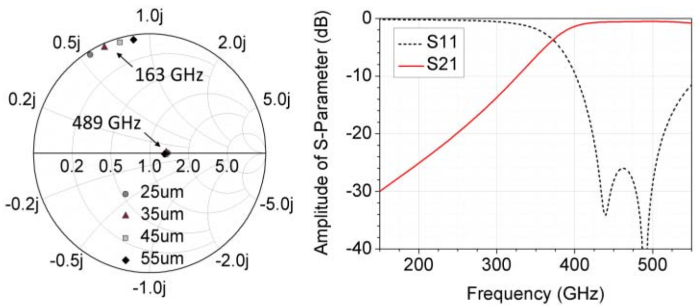


(a) (b)

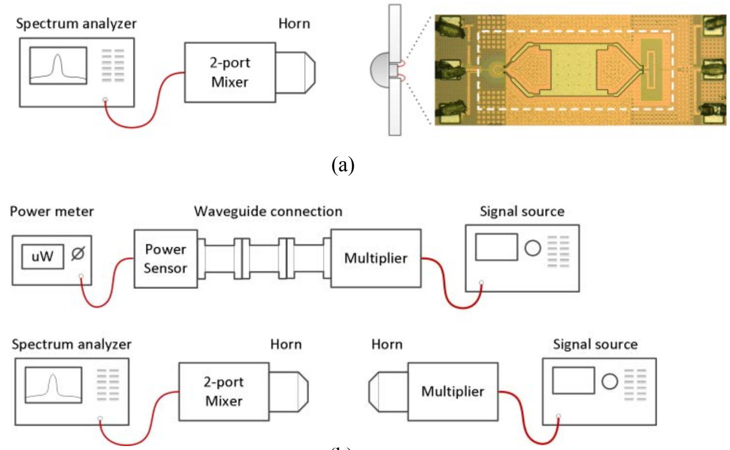
Fig. 2. EM simulation about the SIW together with the MST. (a) Current distribution at the fundamental frequency (163 GHz). (b) Electronic field distribution at the third harmonic frequency (489 GHz).



(a) (b)

Fig. 3. Simulated results about the SIW together with the MST (a) Input impedance. (b) S-parameter.

harmonic frequency. This is not trivial when the third harmonic power is extracted from a symmetrical topology because both the fundamental and the third harmonic signals are in differential mode. In this work, the SIW-based HPE can optimize the tripler load impedance at both the fundamental frequency and the third harmonic frequency. Fig. 1 (b) shows the structure of the SIW-based HPE. The HPE is composed of several sections including a differential SIW in the center, microstrip-SIW transitions (MST) and the matching microstrips between the MST and the HPE input/output ports. At the fundamental frequency, the differential SIW works in microstrip mode and is equivalent to a differential inductance. Fig. 2 (a) shows the simulated current distribution in the SIW at the fundamental frequency (163 GHz). The current goes from the positive input port to the negative input port and virtual ground exists in the middle line of the SIW. The simulated equivalent inductance and Q factor of the differential SIW together with the MST at 163 GHz are 50 pH and 28.2, respectively. At the third harmonic frequency, a TE mode with differential field distribution is excided in the SIW. The SIW and the MST form a traveling wave signal path. Fig. 2 (b) shows the simulated electronic field in the SIW and the MST at the third harmonic frequency (489 GHz). It is observed that a differential TE wave is excited in the differential SIW. Thanks to the different electromagnetic field modes in the SIW at different harmonic frequencies, optimal design can be performed separately for the HPE input impedance at the fundamental frequency and the third harmonic frequency. This can be proved by Fig. 3 (a). Fig. 3 (a) shows the simulated input impedance of the SIW together with the MST when length of the MST is changed. At the fundamental frequency, the equivalent inductance increases with the MST length, while at the third harmonic frequency, the input impedance is constant.



(a)

(b)

Fig. 4. (a) Test setup, PCB assembly and chip photograph. (b) Power calibration.

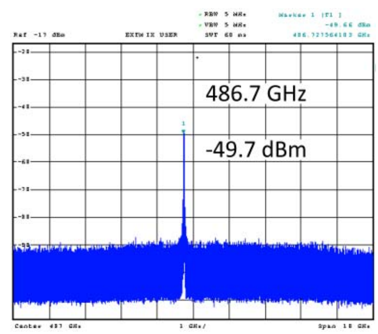


Fig. 5. Measured output spectrum, before accounting for losses.

Besides providing optimized load impedance to the tripler at both the fundamental frequency and the third harmonic frequency, the SIW-based HPE also provides a low loss signal path for the extracted third harmonic power and suppresses unwanted lower order harmonic leakage. Simulated S-parameter of the SIW together with the MST is shown in Fig. 3 (b). The result indicates a high-pass filter frequency response. At 489 GHz, the simulated loss is 0.5 dB. Reflection is lower than -10 dB above 400 GHz. At 163 GHz, S_{21} is lower than -29 dB.

III. Measurement

The radiating source is designed and fabricated in 40 nm CMOS. Fig. 4 (a) shows the chip photograph, the PCB assembly of the chip and the test setup. The core area of the chip is 0.122 mm^2 (dashed line). The backside of the chip is attached on a hemispherical silicon lens with 2 mm diameter and wire-bonded on a FR4 PCB. The THz signal is radiated through the lens. The frequency and EIRP of the chip are measured by a spectrum analyzer with an external two-port mixer aided with a

TABLE I

COMPARISON WITH STATE-OF-THE-ART SIGNAL SOURCES ABOVE 400 GHZ

Ref.	Freq. (GHz)	Tuning Range (%)	Output Power (dBm)	EIRP (dBm)	DC power (mW)	DC-to-THz efficiency (%)	Technology	Measurement
This work	475.2-510.9	7.5	-15.3	-4.1*	17.1	0.173	40nm CMOS	Antenna
[1]	539.6-561.5	4.1	-31	-	16.8	0.005	40nm CMOS	Probe
[2]	519-536	3.3	-11	25 #	156	0.051	130nm BICMOS	Antenna
[3]	559.1-577.6	3.3	-39.7	-34.3	21.4	0.0005	28nm CMOS	Antenna
[4]	485.1-510.7	5.3	-16.6	-	425	0.005	90nm BICMOS	Probe
[5]	540-550	1.9	-9	24.4 #	1300	0.013	65nm CMOS	Antenna
[6]	538.7-559.9	3.8	- 24	-	172	0.002	65nm CMOS	Antenna
[7]	482	-	-7.9	-	61	0.266	65nm CMOS	Probe

* On-chip antenna is coupled with a hemispherical silicon lens with 2 mm diameter.

\# On-chip antenna is coupled with a hyper-hemispherical silicon lens with 15 mm diameter.

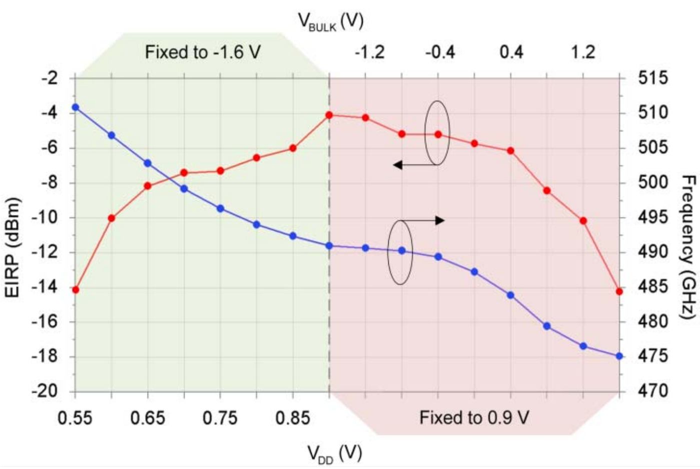
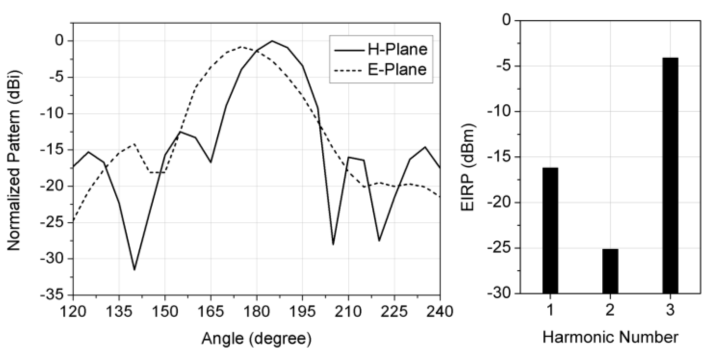


Fig. 6. Measured frequency and EIRP of the radiating source.



(a) (b)

Fig. 7. (a) Measured radiation pattern. (b) Measured EIRP at different harmonic frequencies.

receiving antenna. This setup is calibrated using a commercial source module and a power meter. Fig. 4 (b) shows the calibration procedure. First of all, the THz output power generated by the commercial source module is measured by the power meter through waveguide connection. Then the waveguide at the source module output port is replaced by a horn antenna. After that, the EIRP of the source module can be calculated by adding its output power and the antenna gain together. Next, the DUT is replaced by this commercial source module. Then the commercial source module is measured by the spectrum analyzer in the same way with the DUT. By comparing the commercial source module EIRP and the power value shown on the spectrum analyzer screen, the difference between the EIRP of the DUT and corresponding power value displayed on the spectrum analyzer screen can be known.

Fig. 5 shows the output spectrum of the chip. Fig. 6 shows the measured frequency and EIRP. The left part in Fig. 6 shows results when V_{DD} is changed and V_{BULK} is fixed to -1.6 V. The right part shows results when V_{BULK} is changed and V_{DD} is fixed to 0.9 V. It can be seen that bulk bias tuning technique increases the frequency tuning range. When V_{DD} is 0.9 V and V_{BULK} is -1.6 V, the measured EIRP is -4.1 dBm. According to the simulated antenna gain of 11.2 dB, the output power of the signal source is calculated as -15.3 dBm. Fig. 7 (a) shows the measured antenna pattern. Fig. 7 (b) shows the measured EIRP at different harmonic frequencies. It can be seen that the SIW-based HPE can effectively suppress unwanted lower order harmonic leakage.

IV. CONCLUSION

This work shows the effective use of SIW in a 0.49 THz radiating source as a harmonic power extractor and unwanted leakage filter. The measured equivalent isotropically radiated power (EIRP) of the radiating source is -4.1 dBm at 0.49 THz. The radiating source achieves 7.5% frequency tuning range within 10 dB EIRP variation. To the best of our knowledge, this radiating source has the largest tuning range among Si-based signal generators above 400 GHz.

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